LOCKING A THREAD

IN A CONTROL ROD DRIVE

In nuclear power plants, the level of energy release is governed by large paddle-shaped blades which are inserted into scabbards buried in an atomic pile. The blades are inserted or withdrawn by Control Rod Drive Mechanisms which are controlled by a central control system. This case discusses the design of one part of one of these Control Rod Drive Mechanisms (CRDM). Before treating the specific design problem we shall cover, briefly, the general features of this type of CRDM.

 Written by James D. Thackrey with support from the National Science Foundation.

LOCKING A THREAD IN A CONTROL ROD DRIVE

Operational nuclear power plants use water as a moderator. The water is extremely pure and the water chemistry closely controlled. Metallic ions are virtually non-existent. Because of this fact and the fact that the water is at an extremely high temperature, it is highly corrosive. The CRDM must operate in this corrosive environment at approximately 2000 psi. Reliable seals which might allow a shaft to penetrate a pressure vessel have been difficult to develop, and the corrosiveness prevents using an immersed electric motor. As a result two general types of CRDM have been developed, a magnetic jack and a roller-nut-and-leadscrew device.

Magnetic jack mechanisms operate similarly to linear solenoids, the core being inside the pressure vessel and the coil outside. When the coil is energized, the core closes a fixed gap. This axial motion moves the control rod one increment. Other coils are energized to cause the core piece or a "fixed core" to grip an extension of the control rod. The core grips, moves, and releases while the "fixed core" releases, then grips. Actual gripping of the control rod is either by friction or a set of latch pawls which engage notches in a drive rod.

The roller nut-and-leadscrew type CRDM is equally simple in principle. One such mechanism is shown in Exhibit 1. It doesn't contain the part we are going to design so we will use it only to point out general features. The stator assembly acts as the stator of an electric motor. It is outside the tubular pressure vessel boundary. The rotor is inside the pressure vessel and extends from the radial bearing to the outmotion stop. The rotor only rotates when the control rod is to be raised or lowered. A female "thread" (made of toothed rollers mounted as described below) attached to the rotor extends or retracts the rotationally-fixed leadscrew.

The nut of the nut-and-leadscrew CRDM is a complex assembly. It contains all the parts shown in Exhibit 2, assembled to form the structure shown at the right side of Exhibit 3 and again in Exhibit 4. The water-cooled stator at the left of Exhibit 3 slides over the motor tube, and the "nut" and its retainer plug (foreground of Exhibit 4) fit inside the motor tube. The leadscrew is a square-threaded member (not shown) which passes axially through the motor tube assembly. The base of the motor tube is welded to the reactor dome. As the CRDM functions it lifts the leadscrew/control rod into the motor tube and its extension. The CRDM is engaged by passing electric current through the stator, which causes the pivoted half-nuts to rotate approximately 2½ degrees from the position shown in Exhibit 4. This pivoting causes the toothed rollers to engage the leadscrew thread. Up to this point, we have only passed D.C. through the three-phase stator winding. If the current is caused to be ½ cps alternating current, the field will rotate, and the nut will follow its rotation. The leadscrew is restrained from rotating, so it will move axially to insert or withdraw the control rod which is attached to its end.

In the drive mechanism we are considering the nut is two to three feet long and acts as the armature of an electric motor (the stator is outside the pressure boundary. It is so powerful—electromagnetically

speaking—that it drives sufficient flux through the half-inch wall to cause motor action). The inner part of the nut is split lengthwise into two pivoted halves. The nut-halves (the left and right-most parts in Exhibit 2) engage the leadscrew at one end. The pivot point is chosen so the halves may be forced out of engagement by springs and release the leadscrew. The excursion from disengaged to fully engaged is only a few degrees, being the depth of the square thread on the leadscrew. The nut—the part that engages the leadscrew—consists of banded-tooth rollers in place of a female thread. Two such rollers are in each half of the nut, mounted on ball bearings to reduce driving friction and wear. Exhibit 2 shows the "roller nut" and the clamshell-like segments arms, in one end of which the rollers are mounted. The long ends of the segment arms are magnetic, and are held outward whenever the stator is energized (which is practically all the time). The whole arrangement is grossly inefficient, but power is nowhere cheaper than in a power plant. The reason for such complexity is to ensure that the CRDM is fail-safe. That is, if a power outrage occurs for any reason the segment arms pivot, the rollers disengage, and the leadscrew and the control rod move into the fully inserted position.

There are several other parts which serve special purposes, but we have now come to the part we are concerned with. The operation in which the control rod/leadscrew is dropped is called SCRAM (super-critical reactor accident mode). a SCRAM can occur coincident with disappearance of water from the scabbard. When this occures, the control rod/leadscrew hits bottom hard, and as the parts are long and elastic, it rebounds. If an emergency occures and if you want the control rod in the pile, you certainly can't permit it to bounce back out. A latch is provided to snap in over the top of the leadscrew and prevent its rebounding out once it has scrammed. The latch doesn't hit the end of the leadscrew itself, but rather a part called the rebound stop. The rebound stop screws into the end of the leadscrew. It holds a shoulder on the tie rod (which extends coaxially through the center of the leadscrew and supports the control rod itself) down onto a shoulder in the leadscrew ID. The construction is shown in Exhibit 5.

This case covers the search by engineers at Royal Industries for a method of locking that threaded joint. Any thread subjected to varying axial forces has a strong tendency to unthread. When the forces are large, the part unscrews as if it were driven by an invisible wrench. Hope, wishful thinking, and observations about the angle of repose are equally ineffective in keeping the joint tight; it must be positively locked or it will loosen.

The customer has a few design constraints to impose. Drilling and pinning may not be used because it makes the parts non-interchangeable. The locking device must, if possible, capture and retain the pieces of a broken part—broken anywhere. If parts of the locking device are in tension there must be a guarantee it won't break under stress corrosion, as mechanisms must operate and be guaranteed for twenty-year periods.

Before discussing specific devices we must describe the rebound stop itself, and some additional constraints. The lower end (right end in Exhibit 6) screws into the leadscrew. This end of the part contains a counterbored hole to clear the upper end of the tie rod (a short male hexagon section with a coaxial tapped hole). The two stop pawls normally are clear of the leadscrew

O.D., but when the nut-halves collapse they are forced toward the axis by a strong spring. Thus, when the pawls pass the 2.00 inch diameter shoulder, they snap inward and rest against the 1.31 inch diameter cylindrical section. During actual rebound they bear against the shoulder. Additional functions incorporated in the part are: (1) a wear sleeve which guides the upper end of the leadscrew, (2) a welded-in alnico ring magnet which is used in conjunction with remote switches to indicate leadscrew and control rod position, (3) a tapped hole on the axis to receive a calibrator rod to conform axial position, and (4) bleed holes to allow venting, arranged to permit easy wash-down when the mechanism must be removed "hot" after radioactive service. These bleed holes also bypass the narrow annular clearance space between the wear sleeve and the bore it rides in, to reduce hydraulic forces when the leadscrew assembly moves rapidly as in case of a SCRAM. These hydraulic forces are significant and can delay insertion of the control rod.

In CRDM's of similar design, a tab washer had been used as a locking device. This is a washer the bore of which has a protrusion which fits a keyway milled lengthwise through the shaft; it also contains protruding fingers on its O.D., one of which is bent into a milled notch on the female-threaded member. This design is used to anchor the rings of ball bearings. In CRDM practice, the female-threaded member had contained a notch but the washer was fingerless in order to allow the male thread and washer to stop at any rotational position. When the thread had been made up with the proper torque, the washer was simply deformed locally into the notch. The arrangement is shown in Exhibit 7.

Experience has shown that the crimped washer or tab washer does not always secure the joint tight. For one thing, there was some looseness of parts which could not be taken out during crimping. Moreover the springback of the crimped area, plus the fact that the wedge angle where the initial rotation must occur gives a mechanical advantage to loosening forces may contribute to the looseness after dry SCRAM.

The problem of locking the two parts together was assigned to Jim Thackry, (BS Kansas State, MS University of Delaware). He is an engineer of broad experience who has been with Royal Industries for three years, two of them working on control rod drives. Thackrey worked out a simple conceptual design and turned the detail design over to Harold Craig, a designer who had not worked on nuclear projects. Craig does not have a degree but had two years at Cal Poly and a year's experience. He is a good straightforward designer, but after two or three days he was unable to improve on Thackry's concept of the stop design and thread-locking method. He simply dimensioned it, with the result shown in Exhibit 6. For convenience in describing this and subsequent iterations of the design, we shall assign letters to the various features which are required of the design as follows:

A. Upward-facing chamfers must be provided to "cam" outward (1) locking pawls I haven't mentioned before and (2) the rebound latch pawls during assembly. Both pawls pass the upper (left) chamfer, only the locking pawls pass the second chamfer at the rebound stop face (1.968-1.972 from the lower or right end).

B. The inner diameter under the magnet must be large so as to accommodate a magnetizing pole in case welding or impact demagnetics the alnico ring magnet.

C. The arc-welds must be kept as far away from the magnetic field as possible to allow reliable welding without arc "blowing."

D. A graphite-bearing cast iron wear land (a cylindrical band) is the largest O.D. and guides the leadscrew-rebound stop assembly.

E. An internal water bypass is needed to reduce the hydraulic resistance caused by the small annulus between the wear land and the sleeve it slides in.

F. Means for gripping the rebound stop to tighten it must be provided. (This is the reason for the .437 diameter crosshole in Figure 6).

G. A tapped hole in the part axis must be provided for the customers equipment. A drain is needed in any pocket for washdown of possible radioactive particles.

H. A neck in the center of the part must allow the two rebound pawls (spaced 180° apart) to overlap the stop face. The neck need not be long, but magnet position and the position of the leadscrew are both specified so the overall length is fixed. Since transverse stiffness is not required, the neck is made much longer than is actually required.

I. Rebound stop faces are needed. The corner radius at the transition to the neck needs to satisfy two conflicting requirements: it must be small to get extra footprint area for the pawls, and it must be large to reduce the stress concentration, (consequently, the tolerance allowed is relatively small).

J. A males thread provides axial force to clamp mating parts (see Exhibit 5).

K. A means for locking this male thread to the female thread in the leadscrew is needed. Basically it must lock positively, metal must deform in order for it to unlock.

L. Clearance for a hexagonal protrusion on the mating part (tie rod) must be provided on the axis at the lower end.

The nuclear industry has its own set of "importances," unlike those in most other industries. Reliability, or rather ability to "prove" reliability in advance, overrides all other considerations. A given design may actually be reliable but it cannot be employed without paper proof that it could not fail, or evidence that one could inspect quality into it or "test quality into it." The result is that one of the ground rules of design is to use a proven design if possible. Any design change which could conceivably result in a failure after 10 or 12 years service is not acceptable. I emphasize the word "conceivably," because it is that and not probability which governs whether a design is acceptable or unsatisfactory.

One reason for this situation is that accelerated full scale service tests cost

several months time and perhaps \$100,000 operating expense to run. Yet the total experience of the industry is that smaller and less expensive tests have often been dangerously misleading.

Another reason for the apparently excessive caution is replacement cost. Suppose a part fails in service. It is welded into a fantasically complex structure which takes days to shut down or start up. Moreover, the radioactivity in an operating plant makes servicing even slower and more costly. So a service call on a \$10.00 bearing can shut down a 40 million dollar plant for months, and divert its load to other—already overloaded facilities.

The result is that you don't test much in the nuclear industry, but you think a lot. Moreover, your customer thinks, too. Between you, hopefully, you can find all your errors and come up with something that will work perfectly without testing. Then you test it (assembled in a CRDM) to be doubly sure.

The first design rebound stop, Exhibit 6, was Inconel 718 alloy. It never reached the test stage because the customer thought the heat affected zone where the cladding was laid (to form a wear land) might have reduced impact properties. We couldn't prove it wouldn't so we agreed to change the design.

When it became clear the joint needed more attention, neither Thackry nor Craig were available. The problem was given to Phil Cogswell, who had been in nuclear work for two years. Cogswell was also a self-made designer. He had two years of aeronautical engineering at Cal Aero Engineering and about fifteen years experience in experimental mechanisms as a designer, mechanic, and machinist. He had been designing all his life, but only formally (i.e., on a board) for eight years. Cogswell's numerous sketches were reviewed by Lead Engineer George Pong (twelve years nuclear design experience) and Project Engineer Rolland Thomas (fifteen years nuclear experience). After about two weeks, this team of three selected the design shown in Exhibit 8 and Cogswell spent a week converting the design into a working drawing. In accordance with normal practice, the finished drawing was sent to the customer for his approval before any chips were cut. This design employed a mechanical attachment for the wear land, which became a sleeve. The chamfers and magnet-can design (requirement A, B, and C) were met in the same way as in Exhibit 6. In Exhibit 8, the rebound stop body, item 3, was changed to a titanium alloy which had been used successfully as a rebound step in an earlier design. Dimensions and tolerance could have been arranged so the wear sleeve could be subjected to compressive loads, due to thermal growth (the rebound stop operates at about 200°F, but was designed for 250°F). It was decided that installing it with axial play was preferable. This satisfied requirement D. As shown in Exhibit 8, the magnet portion was attached to the stop portion; the thread was pinned with a crosspin which was then deformed to prevent the joint from unthreading. This makes the two parts a non-interchangeable subassembly, a disadvantage which was recognized but tolerated because the lockpin system is quite good. Even if the pin should break at the bend, both halves would continue to lock the joint. The water bypass system and tapped hole, requirements E and G, were better satisfied in this design than in Exhibit 6.

The locking means for the rebound-stop-to-leadscrew thread, requirement K, consisted of a separate sleeve shaped as

shown in Figure 9. The tangs of the sleeve engage a single slot in the leadscrew, and one of the six slots in the rebound stop. Since slack could be taken up, and spring-back of the tang after it was bent was approximately at right angles to the un-threading motion, this was considered to be a superior locking design. The disadvantage was that if the sleeve should break it was in a position to jam motion of the leadscrew. Ultimately the customer rejected the design because of this disadvantage.

Requirement F, gripping for tightening, was to be handled by supplying a special spanner wrench which engaged the water vent holes. (The wrench will be of special material as steel tools are forbidden in nuclear work. The tiny scrapings left on metal parts by steel tools become the site of corrosion which then proceeds into the parent material).

Between Exhibit 6 and Exhibit 8, a washer-shaped magnetic-iron pole piece was added at each end of the alnico magnet, prior to welding into the non-magnetic inconel housing, for the purpose of ensuring equal magnetic flux at all points in a circumferential direction. This change made the magnetic performance more predictable. This feature—and the design employed here to satisfy requirements H, I, J, and L—are common to all subsequent rebound stop designs.

Although a mechanism using the locking ring was tested, the fact is that the ring could break, in spite of any inspection. Cogswell returned to the drafting board and came up with the design shown in Exhibits 10 and 11. He reviewed the design requirements and sketched concepts for about two weeks before working out the details selected by the team. The bolt of Exhibit 11 screws into a thread in the center of the tie rod. The long slender shank is turned until one of the three holes in the bolt lines up with one of two pairs of slots in the magnet-and-stop-assembly, and a pin is inserted. When the ends of the pin are crimped a tightening torque is supplied to the (now) left-hand thread at the rebound stop/leadscrew joint, requirement J. Even a slight torque is sufficient to maintain the threaded joint tight, and with the tie bolt (Exhibit 11) made of titanium there is no significant thermal problem. The problem with this design was that the maintenance of continuous stress for years in titanium immersed in highly corrosive water represented an unknown. Fabricating the tie bolt of Inconel X, known to be completely free of stress corrosion cracking, would require that the pin slide in the slot to accommodate differential thermal expansion. This creates an unknown wear problem. Thus the design of Exhibits 10 and 11 presents unknown facets, and unknowns are not tolerated in nuclear mechanisms. Another deficiency was that if the lock pin should break where it was not deformed, it could back out and cause interference possibly preventing a SCRAM.

The customer's "shooting down" titanium as a tie bolt material created a further design requirement. Materials for use in nuclear reactors must themselves be corrosion resistant; they may not depend on plating. For stressed parts this effectively rules out any choices except the stellites and Inconel X. Stellites being very long-lead-time materials and not very high strength at that, Inconel X was chosen. Since an Inconel X bolt would have a much higher coefficient of thermal expansion than the titanium rebound stop, some allowance had to be made for thermal motion. The customer suggested replacing the thread at the lower end of the bolt with a spline. Cogswell went back to the drawing

board once again. In a week he had completed analysis and preliminary design, using a hexagonal socket arrangement to allow the tie rod to "breathe" at its lower end under the inevitable thermal cycling. Working out the most satisfactory arrangement at the upper end of the erstwhile bolt took another two weeks.

The final design is shown in Exhibit 12. With Inconel X as a torque rod material, a finer adjustment of rotational position was needed to compensate for the higher torsional modulus of Inconel X as compared to titanium. This was accomplished by making a 36 tooth spline. (Exhibit 13)

Torque flows from the torque rod into the female coupling, through the hex into the tie rod, through the spline into the lead screw female thread. Reverse torque flows into the rebound stop through the upper spline. In assembly, the hex at the end of the torque rod is engaged before the upper spline engages. Torque is applied while the torque rod is slid to axially engage the splines.

A separate locking system is employed for the magnet-to-rebound stop threaded joint. The joint is not subject to high and alternating load during SCRAM. When the lead screw (and control rod, etc.) is bouncing and rebounding, the magnet-to-rebound stop thread needs only accelerate and reverse the magnet assembly mass, so the loads it sees are small. Moreover, the two parts whose axial position depends on the thread, i.e., the torque bar and the bushing or wear sleeve, are not particularly sensitive to axial position. Therefore, a little looseness in the magnet-to-rebound stop thread will not impair function or life of the mechanism. The locking system selected is to use a lock sleeve, itself held by an indexing key to the torque bar. The lock sleeve locks the thread by radial dimples which engage the magnet assembly. This dimpling operation requires a special tool, which complicates manufacture and assembly, but now all design requirements are met.

The student will notice that any of several factors might have shortened the evolution time of this design. More metallurgical data on Inconel 718 or titanium alloy would have helped. So would a more venturesome attitude on the part of the customer. But another factor would have helped even more—a full appreciation at the outset of the magnitude of the task. This is a common lack in design engineering. All the desicison about what is "good enough" are subjective decisions, and sometimes they shift around as the job proceeds. As in the rebound stop engineering case, it may not be easy to decide when the requirements are met. However, it is always most economical of time and energy to settle the design requirements as early and as firmly as possible; then to meet them. If they change, they change.

The rebound stop design took more than 18 months calendar time, and approximately 500 manhours. It was just another engineering problem until the production schedule caused it to become critical. The four designs presented here were each supposed to be the final design; a number of others were sketched or laid out and discarded.

We expect this assembly to survive without attention for 30 years and to perform its function reliably. Neither thought nor cost has been spared to make it so.

Exhibits, ECL 145

Exhibit 1	Schematic drawing of control rod drive mechanism
Exhibit 2	Photograph, CRDM assembly
Exhibit 3	Photograph, CRDM assembly
Exhibit 4	Photograph, CRDM assembly
Exhibit 5	Schematic drawing of rebound stop assembled to leadscrew
Exhibit 6	Drawing, rebound stop (first design)
Exhibit 7	Sketch, tab washer locking arrangement
Exhibit 8	Drawing, rebound stop (second design)
Exhibit 9	Sketch, locking sleeve
Exhibit 10	Drawing, rebound stop (third design)
Exhibit 11	Drawing, bolt (third design)
Exhibit 12	Drawing, final design of rebound stop
Exhibit 13	Drawing, splined lock rod

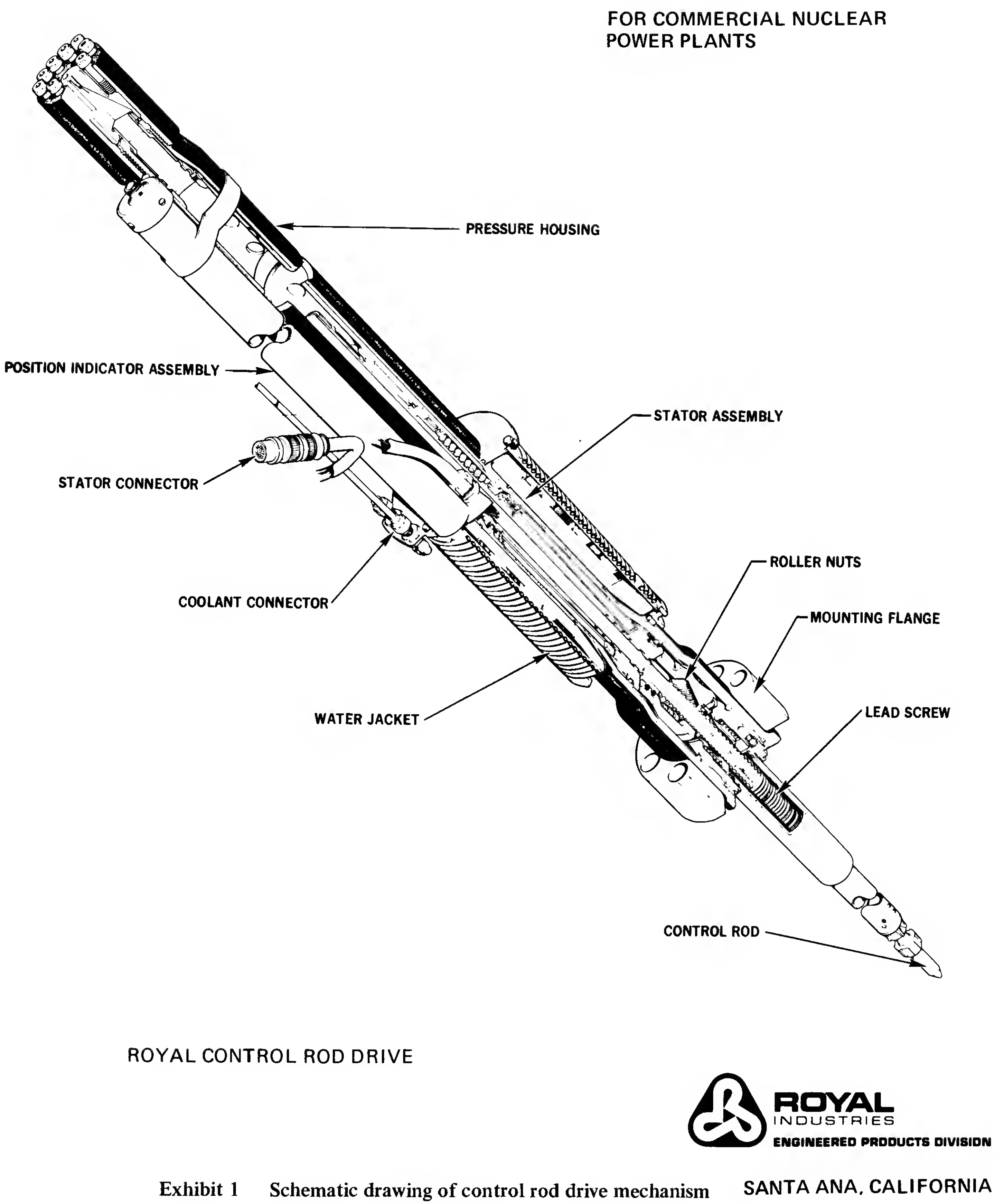

Exhibit 1 Schematic drawing of control rod drive mechanism

Exhibit 2 Photograph, CRDM assembly

Exhibit 3 Photograph, CRDM assembly

Exhibit 4 Photograph, CRDM assembly

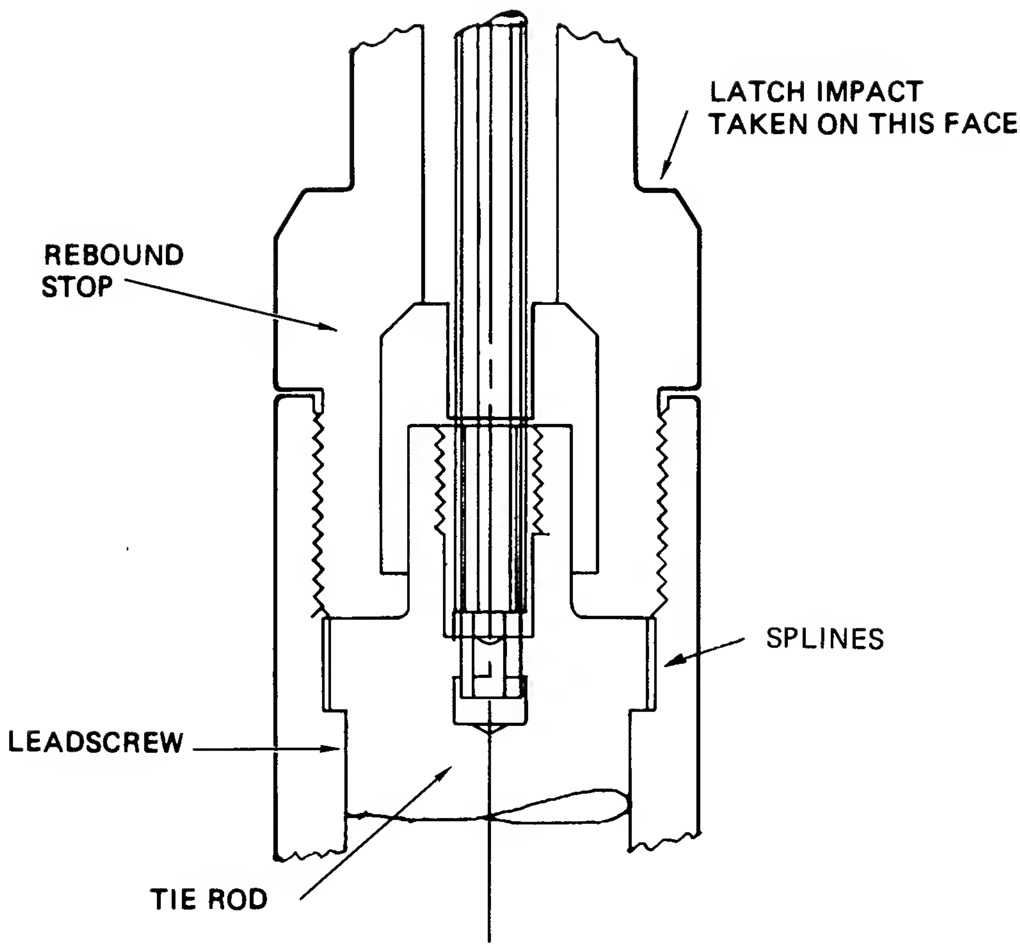

FIGURE 5

Exhibit 5 **Schematic drawing of rebound stop assembled to leadscrew**

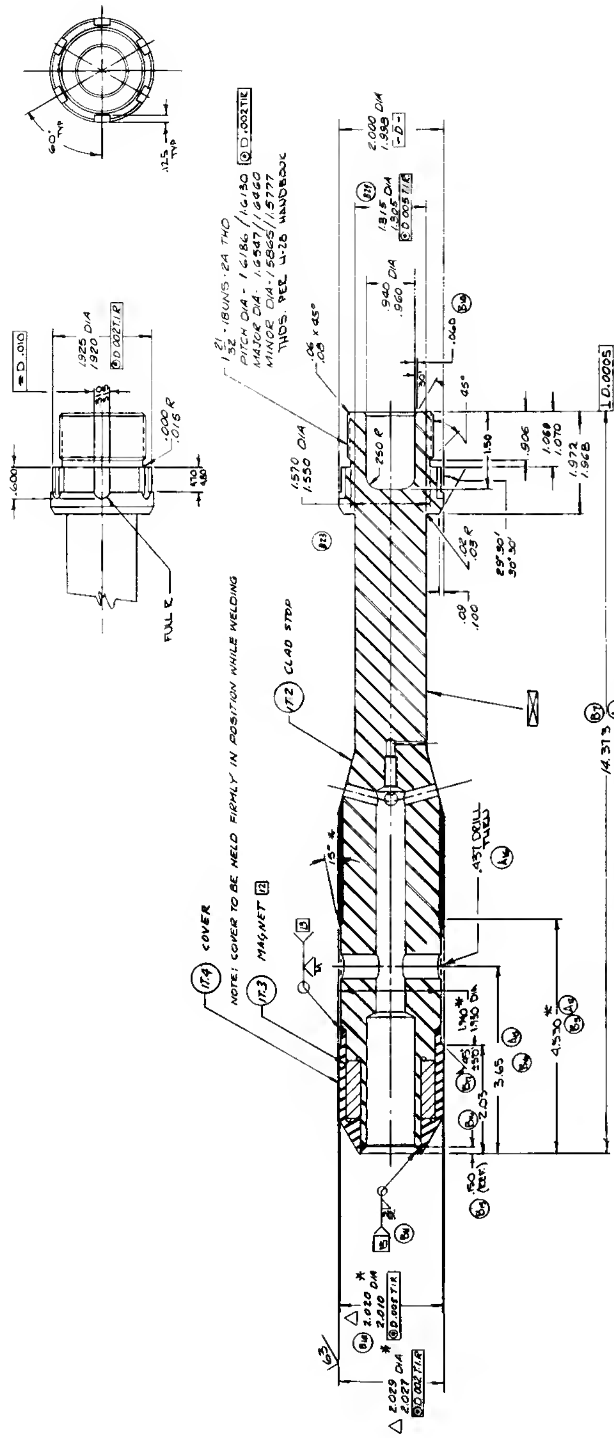

Exhibit 6 Drawing, rebound stop (first design)

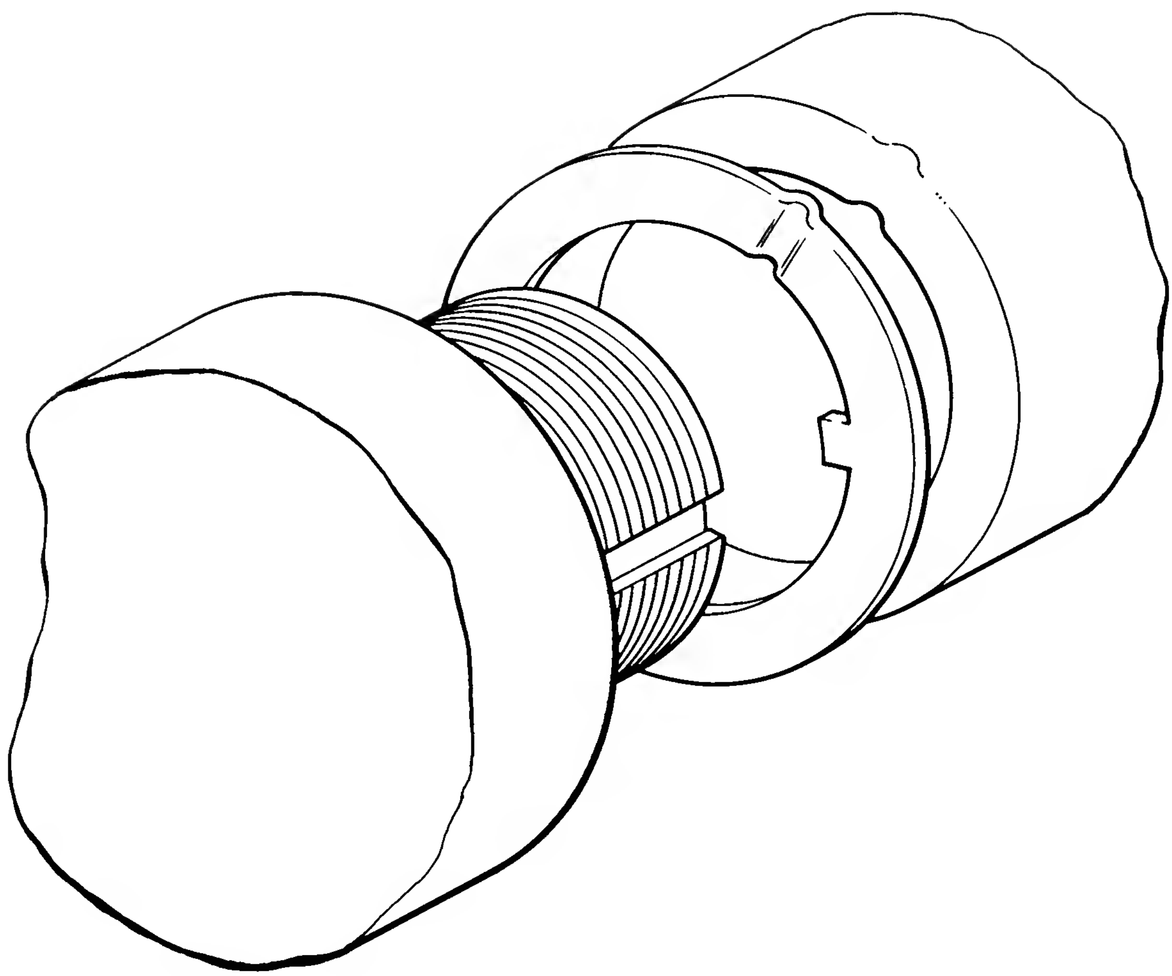

Exhibit 7 Sketch, tab washer locking arrangement

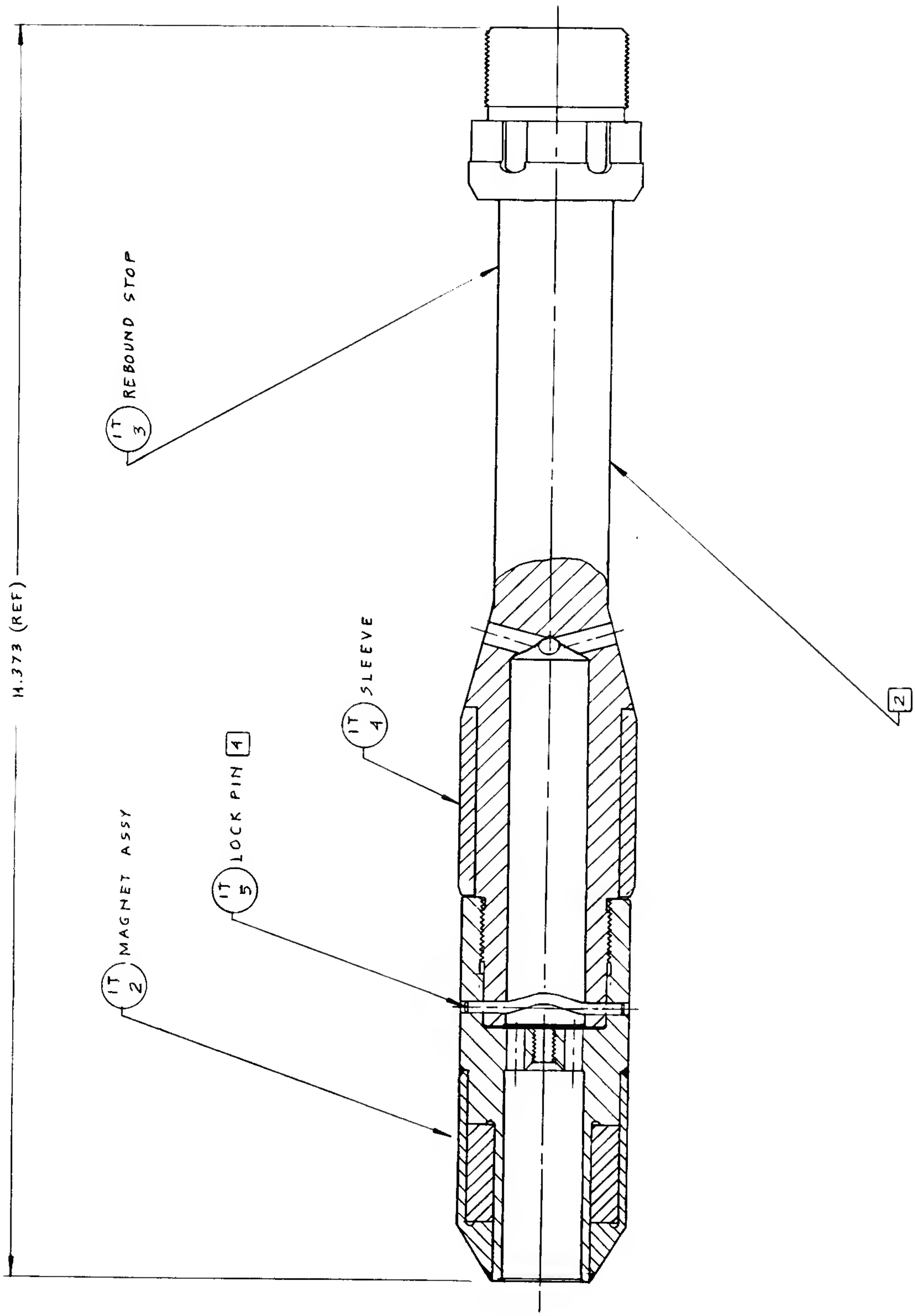

Exhibit 8 **Drawing, rebound stop (second design)**

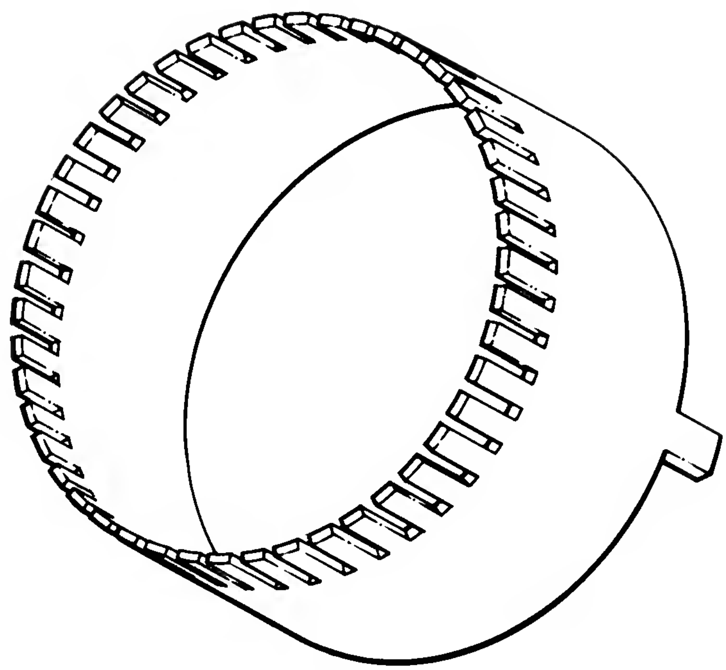

Exhibit 9 Sketch, locking sleeve

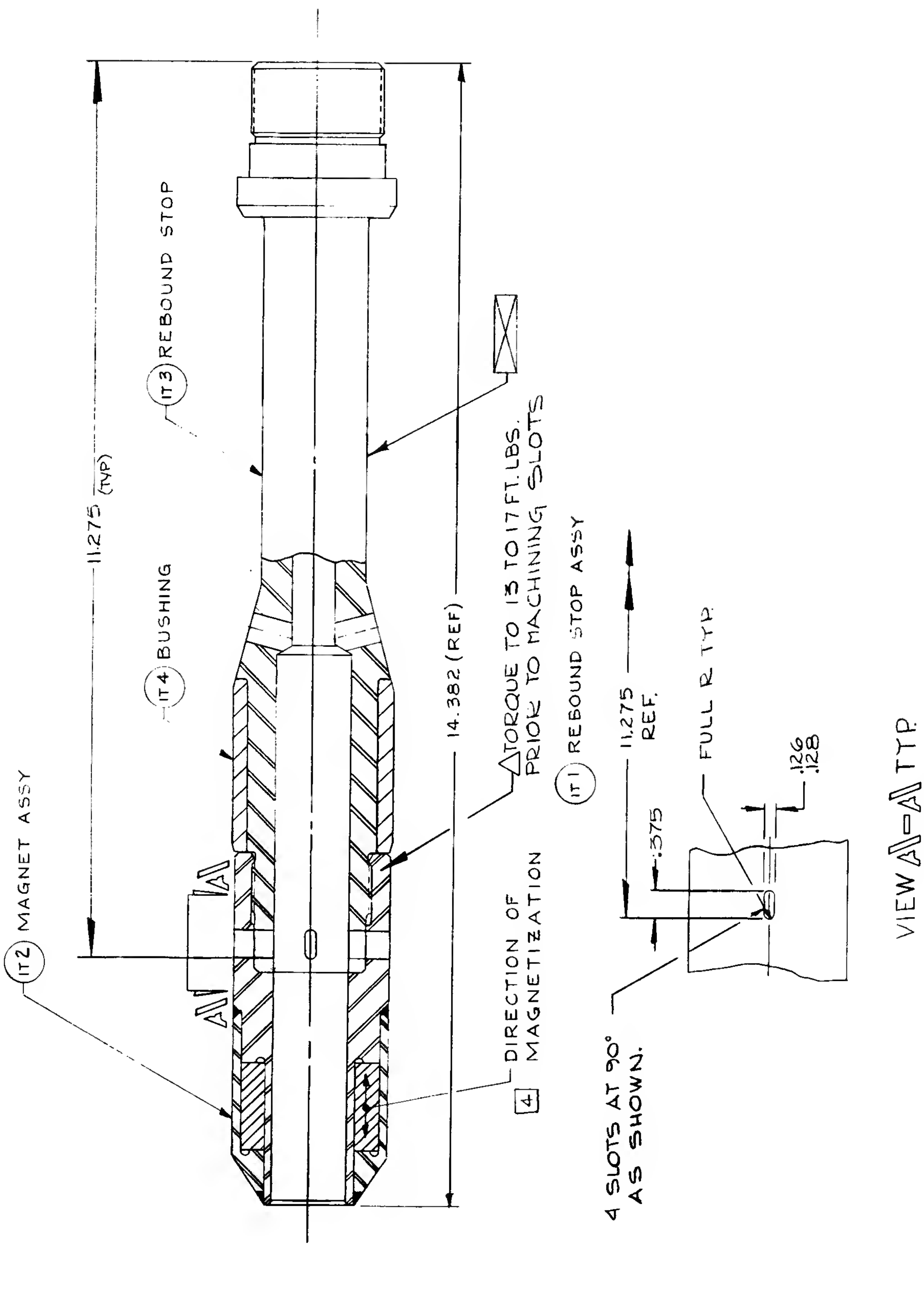

Exhibit 10 Drawing, rebound stop (third design)

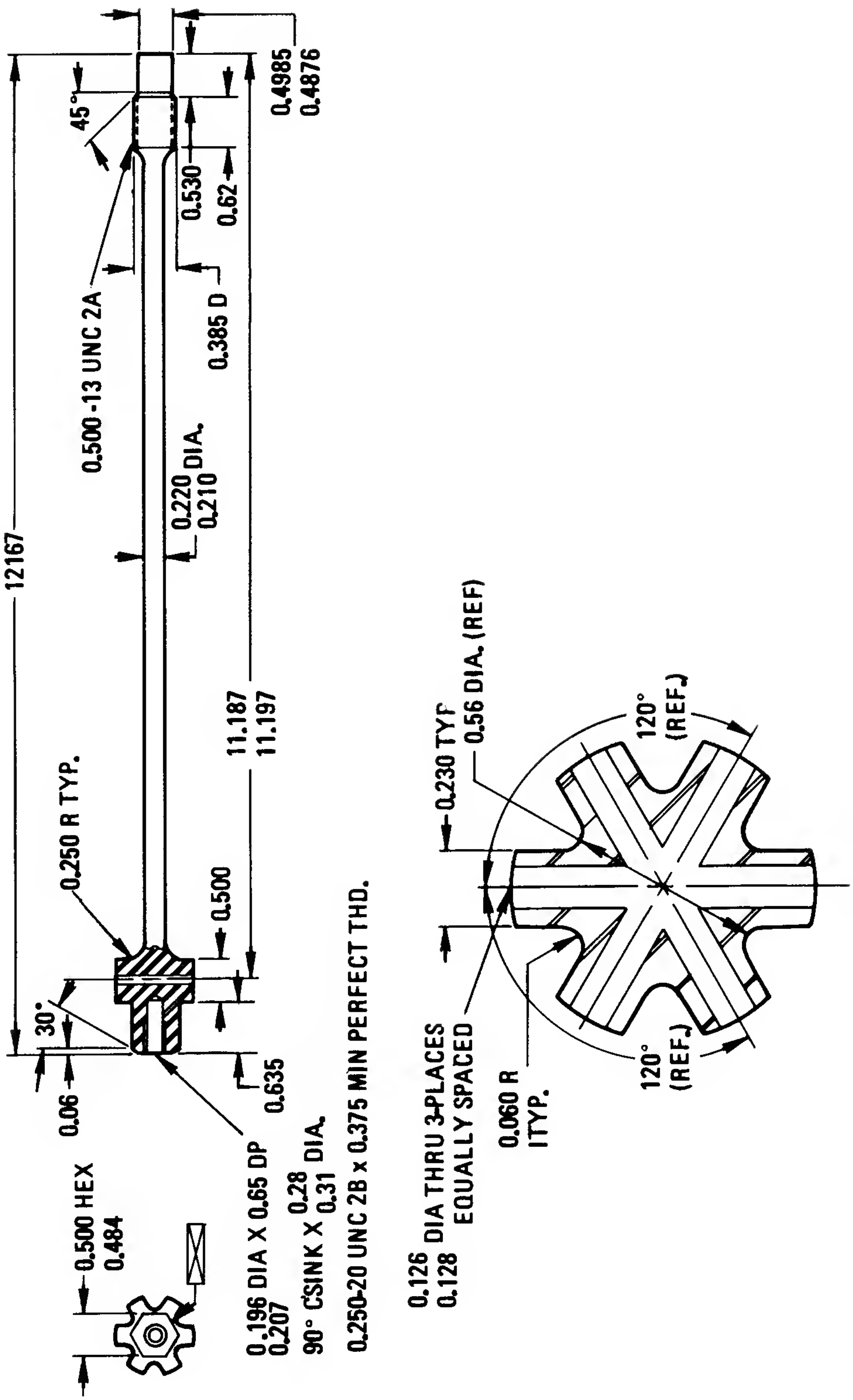

Exhibit 11 Drawing, bolt (third design)

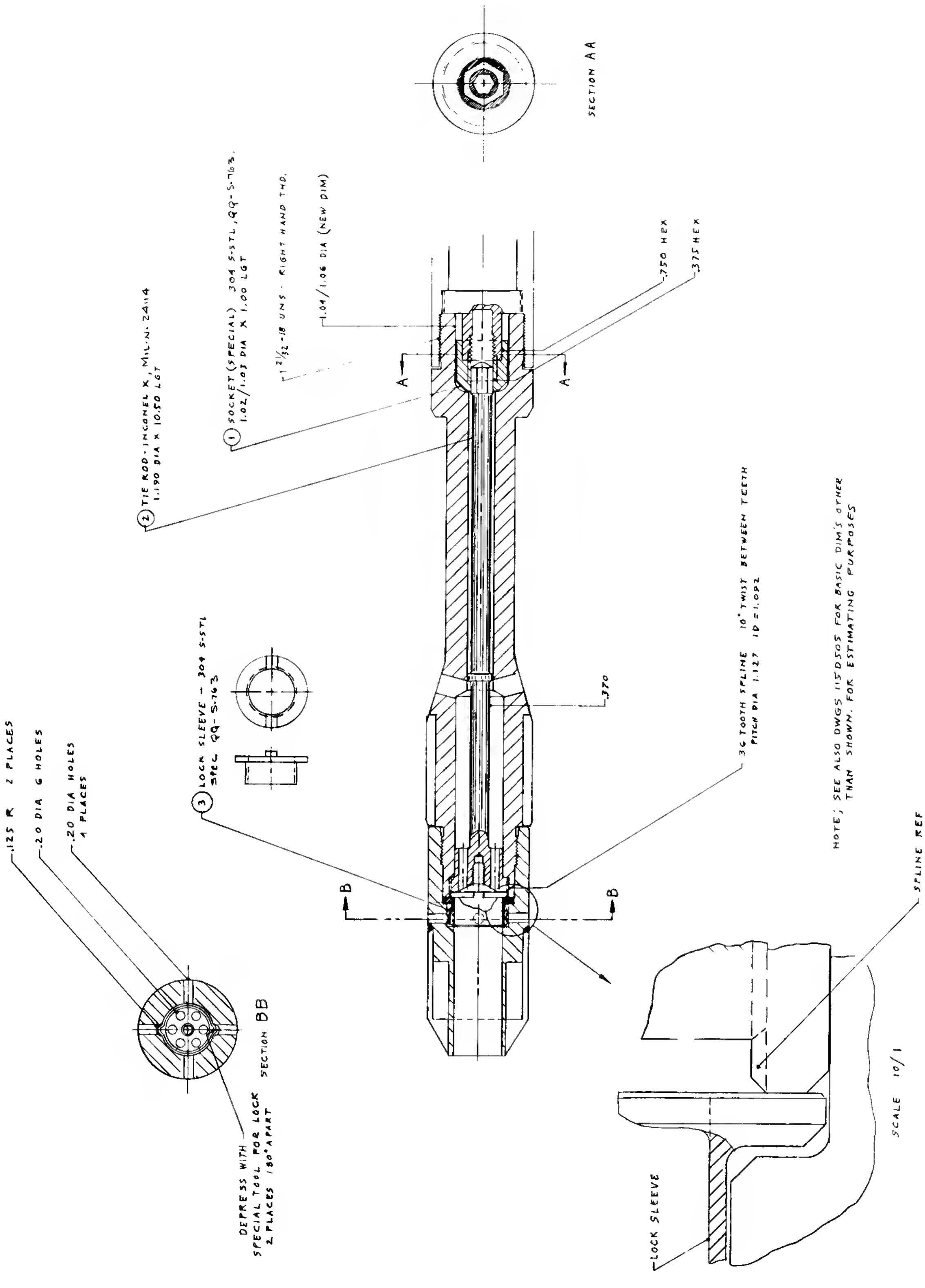

Exhibit 12 Drawing, final design of rebound stop

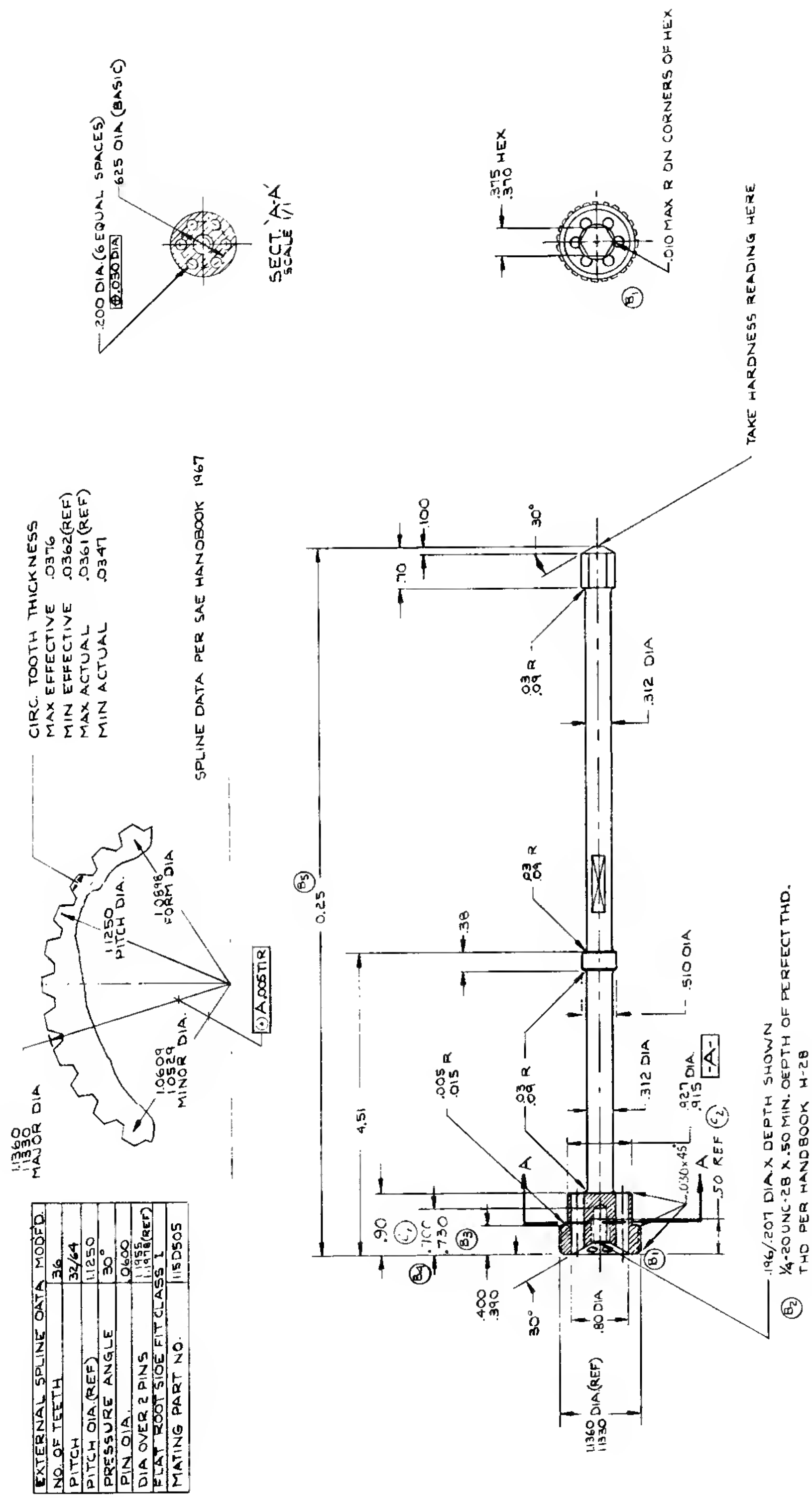

Exhibit 13 Drawing, splined lock rod